Response of the Asian Summer Monsoon Precipitation to Global Warming in a High-Resolution Global Nonhydrostatic Model

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ABSTRACT

This study examined the responses of Asian monsoon precipitation to global warming on the regional scale, focusing on monsoon westerlies and monsoon trough. This is because the Asian monsoon precipitation is closely associated with tropical disturbances. To reproduce convective precipitation and tropical disturbances, this study used outputs of a high-resolution climate simulation. Two sets of approximately 30-yr simulations under present-day (control) and warmer climate conditions (global warming) were conducted by the 14-km Nonhydrostatic Icosahedral Atmospheric Model (NICAM) with explicitly calculated convection. For understanding the spatial pattern of future precipitation changes, a further set of a 5-yr simulation [sea surface temperature (SST) + 4 K] was also conducted. Overall, the Asian summer monsoon was well simulated by the model. Precipitation increased as a result of global warming along the monsoon trough, which was zonally elongated across northern India, the Indochina Peninsula, and the western North Pacific Ocean. This increased precipitation was likely due to an increase in precipitable water. The spatial pattern of the increased precipitation was associated with enhanced cyclonic circulations over a large area along the monsoon trough, although it was difficult to determine whether the large-scale monsoon westerly was enhanced. This enhancement can be explained by future changes in tropical disturbance activity, including weak tropical cyclones. However, over part of South Asia, circulation changes may not contribute to the increased precipitation, suggesting regional characteristics. The regional increase in precipitation along the monsoon trough was mostly explained by the uniform increase in SST, whereas SST spatial patterns are important over some regions.

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1. Introduction

Tropical Asian monsoon precipitation is the major driver of global energy and water cycles. Future changes in tropical Asian monsoon precipitation have been investigated in many previous studies because they are a crucial issue associated with changes in energy and water cycles. Because convective precipitation is essential over the tropical Asian monsoon regions, climatology and future projections of tropical Asian monsoon precipitation should be investigated based on explicit convection-permitting climate experiments. Most related studies have applied global climate models (GCMs) with implicit cumulus convective parameterization. Over Asian monsoon regions, climate experiments using explicit convection calculations are expected to reduce uncertainties associated with cumulus convective parameterizations. An explicit convection-permitting season-long experiment successfully simulated the multiscale Asian monsoon precipitation systems (Oouchi et al. 2009). In addition, an explicit convection-permitting simulation could simulate precipitation characteristics over South Asia using the framework of regional atmospheric models (e.g., Sugimoto and Takahashi 2016; Bhate and Kesarkar 2019). The study by Kodama et al. (2015), which described the experiment of this study, provides a detailed description of the advantages of the explicit expression of moist convection in a GCM.

Large-scale tropical circulations under a warmer climate are characterized by an enhanced atmospheric hydrological cycle, that is, increased precipitation. Held and Soden (2006) described the strengthening of the atmospheric hydrological cycle, particularly over climatologically wetter regions, as a wet-get-wetter pattern. In response to global warming, atmospheric circulation weakens, and water vapor increases over the tropics (Vecchi and Soden 2007). Similarly, changes in Asian monsoon precipitation are projected to increase in response to increase in water vapor (e.g., Kitoh et al. 1997; Ueda et al. 2006; Ogata et al. 2014; Endo and Kitoh 2014). As a result, an enhancement of water vapor transports has been projected.

However, the responses of the Asian monsoon westerlies to global warming remain inconclusive. Some studies have projected intensification of the monsoon westerlies (Kitoh et al. 1997; Ogata et al. 2014; Lee and Wang 2014), whereas others have suggested that they will weaken (Ueda et al. 2006; Sharmila et al. 2015; Sooraj et al. 2015). These inconsistencies may be due to differences in the regions of focus among previous studies.

Moreover, it is considered that the projections in precipitation on the regional scale still have been uneven around the world (e.g., Christensen et al. 2013)

and over the Asian monsoon regions (e.g., Turner and Annamalai 2012). Over the Asian monsoon region, projected regional-scale changes in precipitation can be explained by changes of atmospheric circulation (e.g., Freychet et al. 2015; Kamizawa and Takahashi 2018; Chen et al. 2019). Specifically, an increased precipitation over Southeast Asia with an enhancement of cyclonic circulations were projected along the monsoon trough, which can be associated with tropical disturbance activity (Kamizawa and Takahashi 2018).

Some major high-precipitation areas in the tropical Asian monsoon region corresponded to the monsoon trough, which can be part of the intertropical convergence zone (ITCZ). Generally, monsoon trough has been considered as active transient disturbance region with high precipitation. Spatial characteristics of the monsoon trough are a zonally elongated structure north of the equator around 10°–20°N during the summer monsoon season. Previous studies have investigated the tropical cyclogenesis associated with the monsoon trough (Wu et al. 2012; Molinari and Vollaro 2013; Nakano et al. 2015; Yamada et al. 2017, 2019).

Part of the high precipitation area over South Asia is associated with various tropical disturbances, including monsoon depressions (e.g., Goswami and Mohan 2001; Fujinami et al. 2011; Praveen et al. 2015). Over the Southeast Asian monsoon region, high precipitation is also associated with tropical disturbances, including weaker tropical cyclones (e.g., Takahashi and Yasunari 2008; Takahashi et al. 2009, 2015). Therefore, to understand future changes in precipitation over these regions, we should focus on tropical disturbance activity, including weaker tropical cyclones.

In addition, a poleward shift of strong tropical cyclone activity as a response to global warming has been intensively discussed and is thought to be associated with Hadley circulation expansion (e.g., Kossin et al. 2014; Sharmila and Walsh 2018). This poleward shift is probably associated with the precipitation changes around the monsoon trough and part of the ITCZ. Thus, it is very possible that these changes of spatial pattern in the tropical cyclone activity are associated with future changes in precipitation over the tropical Asian monsoon region.

Observational evidence indicates that tropical Asian monsoon precipitation is strongly associated with tropical disturbance activity; therefore, high-resolution GCMs, which represent tropical disturbances, are recommended for investigating the role of tropical cyclone activity in the responses of Asian monsoon precipitation to global warming. As a category of the high-resolution GCMs, global nonhydrostatic models that explicitly calculate mesoscale convection without convective parameterization are becoming popular (Satoh et al. 2019). These

high-resolution models capture realistic multiscale convective structures that are generally observed in the region of monsoon trough. The Nonhydrostatic Icosahedral Atmospheric Model (NICAM) is one of this type of model, and it has been shown that NICAM reproduces many realistic characteristics of tropical disturbances (Satoh et al. 2014, 2017).

The major objective of this study was to conduct a projection of tropical Asian monsoon precipitation using the NICAM, a global nonhydrostatic model with explicit convection calculations. This is a pioneering study projecting future tropical Asian monsoon precipitation by a global nonhydrostatic model with explicit convection calculations. We also discuss the regional characteristics of future changes in precipitation over the Asian monsoon region, focusing on their association with changes in tropical disturbance activity. Section 2 describes the data and methods used in this study. Section 3 presents our results detailing the Asian monsoon precipitation response to global warming. The role of tropical disturbance activity in precipitation changes and spatial patterns of precipitation in response to global warming is discussed in section 4, and our conclusions are presented in section 5.

2. Data and methods

a. Simulations and observations

We used present-day [control (CTL)] and global warming (GW) experiments simulated by NICAM, which were described in detail by Kodama et al. (2015), Satoh et al. (2015, 2017), and Yamada et al. (2017). NICAM (Tomita and Satoh 2004; Satoh et al. 2008, 2014) is a nonhydrostatic atmospheric general circulation model with explicit moist processes. Our experiments did not use any cumulus convective parameterizations. This study used the 2012 version of NICAM (NICAM.12). Detailed descriptions of the physics schemes of our experiments are shown in Table 2 of Kodama et al. (2015). Although a possible option to additionally use a cumulus scheme might improve subgrid-scale representation (Miyakawa et al. 2018), we chose the merits of the reduction of uncertainty induced by the cumulus scheme. Although NICAM is a global atmospheric model, we coupled it with a slab ocean model by nudging SST to observed one to incorporate the effects of high-frequency ($\sim$ several days) air–sea interactions, which is expected physically realistic SST conditions, such as SST variations associated with a tropical cyclone or an intraseasonal disturbance. In the present study, low-frequency SSTs variations, including seasonal, interannual, and long-term variations, were prescribed using an SST nudging scheme, which cannot

FIG. 1. (a) Simulated climatological SST ($^{\circ}\text{C}$) over the Asian monsoon region during JJA under CTL, which was calculated by the coupled slab ocean model and used as the lower boundary conditions. (b) Differences in SST between present-day and global warming climate conditions (GW – CTL). Data from the 30-yr period from 1979 to 2008 were used for CTL climatology calculations, and data from the 28-yr period from 2075 to 2102 were used for GW climatology calculations.

simulate in the slab ocean model. Besides, Kodama et al. (2015) suggested that NICAM coupling with the slab ocean model simulated a more realistic precipitation pattern than NICAM with the fixed SST. Moreover, the bias of NICAM with the slab ocean model was also discussed (Kodama et al. 2015).

The horizontal resolution of the model used was approximately 14 km with 38 vertical levels, extending to a height of 40 km above sea level. Before analysis, all data were converted to a $1^{\circ} \times 1^{\circ}$ grid (longitude and latitude) because of the vast amount of data. The start date of the simulation was 1 June 1978; the CTL experiment involved 30 summers consisting of June–August (JJA) from 1979 to 2008.

The setting of the GW experiment was the same as that of the CTL except for the SSTs. The specific methods are described by Satoh et al. (2015) and Yamada et al. (2017). Briefly, the SST used for nudging was replaced by warmed SSTs, relative to observed SSTs, to incorporate global warming SST differences obtained in phase 3 of the Coupled Model Intercomparison Project (CMIP3) climate model experiments. Thus, interannual SST variations were the same as those of the CTL. The simulation start date was 1 June 2074. For analysis, we used 28 summers (JJA) from 2075 to 2102 as the GW experiment. Note that we assumed the end of the twenty-first-century condition in CMIP3, which means the years themselves of the GW experiments have no meaning except for the end of the twenty-first-century condition.

We also conducted another 5-yr (2075–79) SST-warming experiment, using the same setting as for the CTL experiment except for the SSTs. Simply, the SSTs used for nudging were replaced by the globally uniform +4-K SSTs, so +4 K was added to all observed SST values. This experiment is referred to as SST + 4 K. Differences between GW and SST + 4 K can be decomposed into the effects of global uniform SST warming and changes in SST spatial patterns, as will be discussed in section 4b.

Because the NICAM coupled with a slab ocean model, the SSTs were somewhat different from the nudging observed values. Figure 1a shows the climatological simulated SST in the model, which was used as a type of lower boundary condition. Because of the effects of nudging toward observed values, the spatial structure of SST was similar to the observation. We also show the spatial pattern in SST warming under the global warming condition (Fig. 1b). Over the tropics, the SST pattern in the CMIP3 experiments under global warming was strongly warming over the equatorial central and eastern Pacific and northern Indian Oceans, which resembles an El Niño-like pattern.

To evaluate the low-level monsoon circulation simulated by NICAM, we use the dataset of the Japanese 55-year Reanalysis Project (JRA-55; Kobayashi et al. 2015; http://jra.kishou.go.jp/JRA-55/index_en.html), including the horizontal winds at the 850-hPa level. We also use satellite-derived monthly rainfall data from the Global Precipitation Climatology Project (GPCP; Adler et al. 2003; <https://psl.noaa.gov/data/gridded/data.gpcp.html>) and daily outgoing longwave radiation (OLR; https://psl.noaa.gov/data/gridded/data.interp_OLR.html) as a convective activity indicator; these datasets include observed global values on a $2.5^\circ \times 2.5^\circ$ grid. For both, we used the 30-yr climatology data from 1979 to 2008.

b. Analysis of tropical storms and tropical disturbances

In this study, we focused on the association between tropical disturbance activity and precipitation changes over the Asian monsoon region. Here, we should define tropical disturbance activity, including weaker tropical cyclones. Specifically, hereinafter we use the terms “tropical disturbance activity” or “tropical disturbances,” which include “severe tropical cyclone,” “tropical storm,” “tropical depression,” and other weaker tropical cyclones.

Following the method of previous studies, we selected perturbation kinetic energy (PKE) as an indicator of tropical disturbance activity. This has been used in the previous studies to measure the activity of perturbation over the midlatitude and tropics (e.g., Arkin and Webster 1985; Matthews and Kiladis 1999; Takahashi 2011; Kamizawa and Takahashi 2018). PKE can be defined as follows:

FIG. 2. (a) Simulated climatological precipitation (colors; mm day^{-1}) and low-level winds (vectors; m s^{-1}) over the Asian monsoon region during JJA under CTL. (b) Climatology over the Asian monsoon region during JJA obtained from JRA-55 and GPCP observations. Original datasets were converted to $1^\circ \times 1^\circ$ grids. (c) Difference between (a) and (b). Data from the 30-yr period from 1979 to 2008 were used for climatology calculations.

$$\text{PKE} = u'^2 + v'^2,$$

where u and v are the zonal and meridional wind, respectively; u' and v' are defined as $u' = u - \bar{u}$ and $(v' = v - \bar{v})$, respectively, where the prime indicates the

FIG. 3. Time (pentad)–latitude cross section in (a),(b) 850-hPa zonal wind (m s^{-1}) and (c),(d) OLR (W m^{-2}) as convective activity index for (top) CTL and (bottom) observations. The 30-yr climatological simulated values from 1979 to 2008 were plotted in (a) and (c), and the 30-yr climatological observed values from 1979 to 2008 were plotted in (b) and (d). The period from pentad 31 to pentad 49 includes JJA.

disturbance component; and $\bar{u}$ and $\bar{v}$ are a 25-day running average. A 25-day high-pass filter was determined to include weak tropical cyclones based on previous studies (e.g., [Chen and Chen 1993](#); [Fukutomi and Yasunari 1999](#)). The evaluation of this method will be shown in [section 4a](#). In this paper, we focused on the area of the northern summer tropical disturbance activity (20°S–35°N). Although PKE is associated with extratropical cyclones over mid- and high latitudes, most mid- and high-latitude regions are beyond the scope of this study.

3. Results

a. Reproducibility of the tropical Asian monsoon

Before analyzing the response of the Asian summer monsoon rainfall to global warming in the NICAM climate simulation, we examined the reproducibility of

Asian summer monsoon rainfall and low-level monsoon circulation. [Figure 2](#) shows spatial peaks in JJA rainfall that were simulated over the western region of the Western Ghats, the head of the Bay of Bengal, the northwestern Indochina Peninsula, the western coast of the Philippines, and the western North Pacific Ocean. Large amounts of rainfall were also simulated over the coastal regions of the “Maritime Continent.” Peaks of rainfall were generally stronger than observed peaks, except over the western North Pacific. Particularly over land regions, simulated summer monsoon rainfall was much stronger than the observation. This is one of the rainfall biases in our experiments within our target region. From detailed observations by the Tropical Rainfall Measuring Mission Precipitation Radar, spatial rainfall peaks were observed on the windward side of the Indian subcontinent, the Indochina Peninsula, and the Philippines

FIG. 4. Longitude–time (pentad) cross section in 850-hPa zonal wind (m s^{-1}) for (a) CTL and (b) observations; 30-yr climatological simulated and observed values from 1979 to 2008 were plotted in (a) and (b), respectively. The period from pentad 31 to pentad 49 includes JJA.

(e.g., Takahashi et al. 2010; Takahashi 2016). The simulation included a spatial peak in precipitation over the western North Pacific, which can partly be understood as precipitation from tropical disturbance activity. This precipitation peak extended farther eastward than the observed rainfall. This eastward expansion is explained by tropical cyclones location bias (Kodama et al. 2015).

We then examined the reproducibility of Asian monsoon circulation in the lower troposphere (Fig. 2). The axis of monsoon westerlies shifted northward by about 5° in latitude. Concurrent with the northward shift of the simulated low-level monsoon westerlies, the spatial peaks of simulated Asian monsoon rainfall shifted slightly northward compared with observations. Also, the South Asia high in the upper troposphere was displaced northward (not shown). The location bias of the monsoon westerly can be due to the warmed bias of the Eurasian continent, which was described as in Kodama et al. (2015) for the NICAM simulation. Besides, similar biases due to fewer clouds were commonly known in the phase 5 of CMIP (CMIP5) climate models (Hirota et al. 2016).

We also confirmed the seasonal meridional evolution of monsoon westerly and convective activity over South

and Southeast Asia (Fig. 3). The monsoon westerly developed from around May to early June (pentads 25–32) along 5° – 15°N . Concurrent with the development of monsoon westerly around, convective activity developed and extended northward, which can be understood as the onset phase of the Asian monsoon. Because of the northward displacement of the monsoon westerly, the simulated convective activity was also displaced northward. As shown in Fig. 2c, the northward displacement of the monsoon westerly and convective activity was observed throughout the summer monsoon season.

We also evaluated the reproducibility of the seasonal eastward expansion of the monsoon westerly (Fig. 4), which characterizes as the formation of monsoon trough (e.g., Takahashi and Yasunari 2006) or the western North Pacific monsoon. The simulated monsoon westerly first appeared over South and Southeast Asia and extended eastward to the western North Pacific by around late June (pentad 35), which agreed with the observed formation of the monsoon trough. However, another eastward expansion of the monsoon westerly was more weakly simulated in mid- and late August (pentads

FIG. 5. (a) As in Fig. 2a, but under global warming climate conditions. NICAM GW experiment results for the 28-yr period from 2075 to 2102 were used for climatology calculations. (b) Differences in precipitation (mm day^{-1}) and low-level winds (m s^{-1}) between present and global warming climate conditions (GW – CTL) were used to examine Asian monsoon responses to global warming. (c) As in Fig. 2a, but for simulated climatological vertical winds at the 500-hPa surface over the Asian monsoon region during JJA under present-day climate conditions. Because NICAM is a non-hydrostatic atmospheric GCM, moist convection is explicitly calculated in the model. Note that positive vertical velocity indicates upward motion. (d) Differences in vertical winds (m s^{-1}) at the 500-hPa surface between the present-day and global warming climate conditions (GW – CTL). Values were multiplied by 10^3 before plotting.

45–47), although the somewhat weakening of monsoon westerly corresponded to the observation.

Although the bias can be observed, the seasonal evolutions of the monsoon westerly and convective activity were simulated in NICAM. Specifically, timings of monsoon onset and peak almost corresponded to the observation. Sperber et al. (2013) showed that too-late monsoon onset over South Asia in CMIP3 and CMIP5 models, although we cannot simply compare an atmosphere–ocean coupled climate model and an atmospheric model. Thus, these evaluations suggest that the Asian monsoon system can be simulated in the model, although the monsoon system is generally tricky to simulated in climate models. In addition, a wet bias was found over the equatorial Indian Ocean during the summer monsoon season. This bias is still one problem on the Asian monsoon simulation, although this bias was improved from the previous version of NICAM (e.g., Oouchi et al. 2009). Thus, our climate simulation can contribute to understand the Asian monsoon in terms of a high-resolution

experiment, although we have many subjects to improve the reproducibility more.

b. Rainfall response to global warming

This section examines the response of Asian monsoon to global warming as simulated by NICAM. Figures 5a and 5b show the climatology of the Asian monsoon under global warming conditions and differences in rainfall and low-level circulation over the Asian monsoon region between the CTL and GW experiments.

Area-averaged precipitation over the Asian monsoon region (40°E – 180° , 20°S – 50°N) increased by $0.268 \text{ mm day}^{-1}$ (5.85% relative to the present-day climatology). This increase in precipitation over the Asian monsoon is consistent with the results of previous studies (e.g., Ogata et al. 2014).

An increase in simulated rainfall was identified along the latitudinal band from 10° to 25°N across the Arabian Sea, Indian subcontinent, Bay of Bengal, Indochina Peninsula, South China Sea, and western North Pacific.

Part of the distinct increase in rainfall was calculated over a large area of the monsoon trough of northern Indian monsoon, Southeast Asian monsoon, and western North Pacific monsoon regions. The increase was also found over southern India, where the orographic precipitation associated with the monsoon westerly is dominant. A decrease in simulated rainfall was found along the equator region from the equatorial Indian Ocean and part of the Maritime Continent to the equatorial central Pacific. Rainfall also decreased over the western edge of the subtropical high over the western North Pacific.

Monsoon westerlies appear to have been enhanced over the southern Indochina Peninsula and the Philippines, whereas monsoon westerlies weakened over South Asia. This result indicates that it was very difficult to determine whether monsoon westerlies were enhanced, despite reports in several previous studies that changes in rainfall were associated with changes in monsoon westerlies.

Concurrent with the increase in rainfall, signals of cyclonic circulation anomalies were simulated along the monsoon trough, where cyclonic circulation is dominant as a basic low-level flow. This enhancement of cyclonic circulation can explain the increase in precipitation along the monsoon trough. On the other hand, the changes in monsoon westerlies could not simply explain the increase in precipitation. This result is consistent with observed interannual variation in precipitation along the monsoon trough (Takahashi et al. 2015). Besides, over southern India, the changes in atmospheric circulation could not explain the increase in precipitation.

Anticyclonic anomalies were simulated over the subtropics, where precipitation decreased. Positive rainfall anomalies along the monsoon trough can be associated with the decreased precipitation over the subtropics regions. Anomalous divergence tendencies of 850-hPa winds are associated with the decrease in precipitation along the equatorial Indian Ocean and part of the Maritime Continent. Climatologically, the equatorial Indian Ocean and part of the Maritime Continent, where precipitation decreased, are near the southern rim of the Asian monsoon precipitation area during JJA in the CTL experiment (Fig. 2). These changes in spatial patterns can partly be understood as a concentration of the high-precipitation regions on the monsoon trough.

c. Relationship between projected changes in vertical winds and precipitation

Tropical mean circulation weakening has been projected and explained by several previous studies (e.g., Vecchi and Soden 2007). In current study, we analyzed projected changes in vertical winds at the 500-hPa level

to elucidate the changes in Asian monsoon precipitation due to global warming.

The climatological distribution of the simulated vertical winds (Fig. 5c), which is generally consistent with the spatial pattern of precipitation. For example, spatial peaks in vertical wind were observed over the windward sides of the Indian subcontinent, the Indochina Peninsula, and the Philippines. Broad upward motions were also found over the western North Pacific. As a part of Asian monsoon circulation, upward motion was simulated in a few areas over the Asian monsoon landmass, and downward motion in a few areas over the southern Indian Ocean.

We then analyzed the responses of 500-hPa vertical winds to global warming (Fig. 5d). Strengthening and weakening of vertical winds were simulated over the Asian monsoon region (40°E–180°, 20°S–50°N), with an average change of $-1.04 \times 10^{-4} \text{ m s}^{-1}$ (3.88% weaker than the present-day climatology); this finding is consistent with those of previous studies, which reported weakening of tropical mean circulation in response to global warming.

The spatial pattern of responses showed distinct, zonally expanded signals over the Asian monsoon region. Enhanced upward motion was found along a latitudinal band of approximately 10°–20°N, which is consistent with the increased precipitation. Concurrent with the enhanced upward motion, anomalous downward motion coexistent north and south of the latitudinal band. These anomalous downward motions indicate reduction in climatological upward motion and are consistent with the decreases in precipitation along the equatorial (from the central equatorial Ocean to part of the Maritime Continent) and subtropical (from the Tibetan Plateau to the subtropical western North Pacific) zonal bands. Notably, the spatial pattern of enhanced upward motion was spatially concentrated, similar to the precipitation changes.

d. Future changes in the seasonal progression of the Asian monsoon

We then examine future seasonal progression of monsoon westerly and convective activity over the South and Southeast Asian monsoon regions (Fig. 6). Future changes of the monsoon westerly were unclear along the axis of the monsoon westerly during the JJA period (pentads 30–48). In addition, monsoon westerly was weakened along the north and south of the axis of the monsoon westerly, which implies no meridional shift of the monsoon westerly due to global warming (Fig. 6a). However, we should continue to investigate the changes in monsoon westerly because NICAM has the position bias of the monsoon westerly. Concurrent with the changes of the monsoon westerlies, the convective activity was enhanced along the monsoon trough and suppressed along the

FIG. 6. As in Fig. 3, but for (a) differences in 850-hPa zonal wind and (b) differences in OLR along the averaged band from 70° to 100°E between present-day and global warming climate conditions (GW – CTL).

southern band of the monsoon trough. These responses of the monsoon westerly and convective activity to global warming was observed throughout the summer monsoon season.

e. Spatial pattern of increased water vapor

This section discusses the spatial pattern of projected increases in water vapor (precipitable water) in response to global warming (Fig. 7). Water vapor changes are regulated by the Clausius–Clapeyron formula, which explains the approximately 6%–7% increase in water vapor that is due to 1-K surface air temperature (SAT) warming under constant relative humidity.

FIG. 7. (a) As in Fig. 2a, but for simulated climatological column-integrated water vapor (precipitable water) over the Asian monsoon region during JJA under CTL. (b) Rate of increase (%) of precipitable water over the Asian monsoon region per 1-K surface air temperature warming at each grid. Increases in precipitable water and SAT were calculated from differences between the CTL and GW experiments. The color gradient indicates an approximately 6%–7% increase in water vapor per 1-K SAT warming, governed by the Clausius–Clapeyron equation under the assumption of fairly constant relative humidity.

In general, our simulation clearly showed future increases in precipitable water, which can be explained by an increase in the water vapor holding capacity of the atmosphere. Increases below 6%–7% were typically simulated over land, which is due to the limitation of evapotranspiration through a shortage of soil moisture under warming conditions. These basic projections of precipitable water changes are consistent with those of the previous studies.

We observed distinct regional features in the increases in precipitable water projected in our simulation (Fig. 7b). The increase in precipitable water greatly exceeded the 6%–7% increase over the ocean. Figure 8 shows a histogram of increased precipitable water; 9%–10% increases in precipitable water were simulated most frequently over the Asian monsoon region (40°E–180°, 20°S–50°N), and values sometimes exceeded 10%.

FIG. 8. Histogram of the increasing rate of precipitable water over the Asian monsoon region (40°E – 180° , 20°S – 50°N) per 1-K surface air temperature warming at each grid, which are the same values plotted in Fig. 6.

Particularly over the monsoon trough and other regions where precipitation increased, increases in precipitable water were much greater than 6%–7%. Given that future changes in global mean precipitable water are expected to reach approximately 6%–7%, those over the ocean should exceed 6%–7% to compensate for the limited increase in evapotranspiration over land. In our experiments, regions with greater increases in precipitable water generally corresponded to regions of increased precipitation. This result indicates not only that precipitable water largely increases over the ocean but also that the spatial pattern of increase in precipitable water, particularly over the ocean, may play an essential role in the spatial pattern of precipitation changes.

We then examined projected changes of meridional structures in precipitation and precipitable water over the Southeast Asia and western North Pacific longitudinal band (90° – 140°E ; Fig. 9). Under warming conditions, both precipitation and precipitable water were concentrated on the monsoon trough rather than the northward displacements of the high precipitation area. A similar tendency in convective activity can be found over a South Asia longitudinal band (60° – 100°E ; Fig. 6). The spatial pattern of projected changes in water vapor will be discussed in section 4a.

4. Discussion

a. Westward-propagating tropical disturbances along the monsoon trough

This section examines changes in rainfall during JJA and their association with dynamic (circulation) effect changes. As discussed in section 1, dynamic effects are

FIG. 9. Meridional structure of (a) climatological precipitation and (b) precipitable water along the Southeast Asia and western North Pacific longitudinal band (90° – 140°E). The solid lines denote CTL, and the dashed lines denote GW. For precipitable water, we display the anomaly values from the averaged values over the Southeast Asia and western North Pacific longitudes region (90° – 140°E , 20°S – 50°N).

also important for explaining the changes in rainfall on a regional scale (e.g., Freychet et al. 2015; Kamizawa and Takahashi 2018; Chen et al. 2019). As shown in section 3b, although the changes of the large-scale monsoon westerly were not clear, cyclonic circulation was clearly enhanced along the monsoon trough. To understand the enhancement of cyclonic circulation along the monsoon trough, we analyzed changes in tropical disturbance activity.

1) RESPONSE ALONG THE MONSOON TROUGH

Climatologically, the monsoon trough is the major route of westward-propagating tropical disturbances

FIG. 10. (a) Longitude–time cross section of the simulated precipitation (mm day^{-1}) along the zonal band of the Asian monsoon (10° – 25°N). (b) Simulated PKE ($\text{m}^2 \text{s}^{-2}$) along the zonal band of the Asian monsoon, which was defined in section 4. The period of (b) is the same as that of (a).

(e.g., Wang and Rui 1990; Chen and Chen 1993; Fukutomi and Yasunari 1999). Seasonal mean precipitation along the monsoon trough can therefore be associated with the tropical disturbance activity (e.g., Goswami and Mohan 2001; Takahashi et al. 2015).

To verify the reproducibility of westward-propagating tropical disturbances simulated by NICAM, we produced a longitude–time cross section of the simulated precipitation and PKE along the monsoon trough at 10° – 25°N (Fig. 10). Transient westward-propagating precipitation was found along this zonal band from 80°E (Bay of Bengal) to 180° (western North Pacific), which corresponds to westward-propagating precipitation systems reported in Takahashi et al. (2015). This result implies that accumulated PKE can be a measure of the tropical disturbance activity. Thus, NICAM captured signals of dominant tropical disturbances with precipitation along the monsoon trough. Note that anchored precipitation signals over the western coast of the Indian subcontinent and the Indochina Peninsula represented orographic precipitation associated with the monsoon westerly. Compared with the monsoon trough region, westward-propagating precipitation signals over the South Asian monsoon around 60° – 90°E were often unclear. This inconsistency is discussed in section 4a(3).

The climatological spatial pattern of PKE (Fig. 11, top panel) is generally similar to that of the tropical cyclone track density simulated by NICAM (Yamada et al. 2017; Satoh et al. 2018). In particular, spatial peaks were found east of Taiwan. Tropical disturbance activity over the South and Southeast Asian monsoon regions, which include few tropical storm regions, are consistent with those described in previous studies (e.g., Wang and Rui 1990). Thus, we reconfirmed that PKE can be a measure of tropical disturbance activity in our target areas.

Positive signals of PKE change clearly corresponded to increased precipitation, mainly along the monsoon trough, consistent with enhanced tropical disturbance activity (Fig. 11, bottom panel), although this correspondence was not clear over the southern Indian monsoon region [see also section 4a(3)]. Notably, correspondence between projected changes in PKE and precipitation was simulated not only along the monsoon trough but also over the western North Pacific, East Asia, and Maritime Continent. For example, enhancement of the western edge of the subtropical high, which can be understood as westward expansion of the subtropical high, was associated with a decrease in precipitation over western Japan. This finding implies that changes in atmospheric

FIG. 11. (top) Simulated PKE, which was defined in section 4 over the Asian monsoon region. Over the tropical region, climatologically high PKE implies active tropical disturbance, which can include tropical storms. Over the mid- and high latitudes, PKE basically shows extratropical cyclone activity. In the northern winter, active storm track activity can be observed east of the continents (not shown). We calculated PKE from 6-hourly outputs, and then we averaged for JJA periods. In addition, because we used the disturbance components (see the definition of the disturbance component in section 4), the climatologically strong winds (e.g., the Somali jet) were not included. (bottom) Differences in PKE ($\text{m}^2 \text{s}^{-2}$) between the CTL and GW conditions. The colors show the difference between them. The contours denote the change rate relative to the CTL climatology (Fig. 7a). The hatched area indicates that the difference is statistically significant at the 95% confidence level (two-sided Student's t test).

circulations, which can be interpreted as changes in the dynamical component, can explain the regional pattern of future precipitation changes.

Previous studies on the poleward shift of the latitude of the lifetime maximum intensity of tropical cyclones in the western North Pacific as a response to global warming (e.g., Kossin et al. 2014; Sharmila and Walsh 2018). The spatial pattern of PKE changes in our analysis were generally consistent with the previous studies on the change in the track density of the strong tropical cyclone. To understand roles of tropical disturbance, including weaker tropical cyclones, on total precipitation and their future changes, we need more detailed analysis on the contributions of precipitation as a function of tropical cyclone intensities.

2) RESPONSE OVER THE SOUTH ASIAN MONSOON REGION

The responses of precipitation and low-level circulations to global warming were somewhat different between

over the monsoon trough and part of the South Asian monsoon regions. Climatologically, precipitation variability is closely associated with the strength of the monsoon westerly, particularly southwestern India, which is different from that along the monsoon trough. Over South Asia, westward-propagating rainfall signals were not so often (Fig. 10). An enhancement of tropical disturbance activity was observed in northern India was observed (Fig. 11, top panel), which was corresponded to the rainfall increase (Fig. 5b). However, these was no clear correspondence over southern India. These climatological differences in precipitation systems were likely to be associated with the different responses.

3) THERMODYNAMIC AND DYNAMIC EFFECTS

On Asian monsoon and global scales, changes in water vapor, which can be interpreted as the thermodynamic component, explain changes in overall precipitation.

However, we showed that the spatial pattern of increased water vapor may be associated with changes in low-level circulation in this study, suggesting that the spatial pattern of water vapor (thermodynamic component) can be partly controlled by changes in atmospheric circulation (dynamic component).

Recently, a relationship between water vapor and atmospheric circulation in the context of global warming was discussed. Noda et al. (2019) by analyzing the NICAM simulation showed that upward motion only increases in the region where relative humidity increases over the tropics, suggesting that changes in atmospheric circulation partly interact with water vapor changes. These results were consistent with our result focusing on the Asian monsoon regions.

The spatial pattern of projected changes in vertical motion (Fig. 5d) was very similar to that of PKE (Fig. 11, bottom panel), suggesting that future changes in vertical motion were closely related to the changes in tropical disturbance activity, which was detected mainly along the monsoon trough. Thus, enhanced tropical disturbance activity can presumably explain changes in precipitation over the Asian monsoon regions along the monsoon trough through the collaboration between thermodynamic and dynamic effects.

b. Effects of SST warming pattern on the spatial pattern of response

This section discusses the spatial pattern of the precipitation response to global warming, characterized as the precipitation increase along the zonal band from South Asia to the western North Pacific.

The spatial pattern of precipitation differences between the CTL and GW experiments may be partly explained by the influence of this El Niño-like SST pattern (Fig. 1b). To understand the differences in responses to CMIP3 (uniform SST warming + El Niño-like SST warming) and uniform SST warming patterns, we also analyzed 5-yr SST + 4 K experiments (numerical design provided in section 2a). Because of the very high computational cost of NICAM, we could not run another 30-yr-long experiment. We therefore compared the CTL versus SST + 4 K and GW versus SST + 4 K experiments using 5-yr periods for all three experiments, prescribing the same interannual variability. Five-year simulations reduce a specific response in a specific year, which can climatologically evaluate differences in sensitivity of the Asian monsoon to assumed global warming conditions, compared with a few samples. Our comparison of the GW and SST + 4 K experiments required normalization of the changes in precipitation and 850-hPa winds by global mean Δ SAT warming values, where Δ indicates the warming response relative to the CTL experiments.

1) UNIFORM SST WARMING EFFECT

Figure 12 shows the different influences of the spatial pattern of SST warming. Figures 12a and 12d are as in Fig. 5b, but for a larger domain, and we evaluated by a statistical test. Increased precipitation was found along the monsoon trough and part of the ITCZ, which was mostly statistically significant. Similarly, differences between the SST + 4 K and CTL experiments show increased precipitation over a similar regional extent (Fig. 12b), although the statistically significant signals were limited. We could obtain these similar responses in precipitation and winds along the monsoon trough, which implies that increased precipitation along the monsoon trough of Southeast Asia and western North Pacific is due to globally uniform SST warming.

As major exceptions, opposite responses were found over South Asia and part of the equatorial central Pacific. The uniform SST warming effect could not explain the different responses over part of South Asia and part of equatorial central Pacific, suggesting regional differences in the responses over the Asian monsoon region where climatological precipitation characteristics are various. Although East Asia was not a major focus of this study, precipitation and wind responses tended to have the same sign (Figs. 12a,b,d,e). Nevertheless, responses over East Asia were weaker than those over Southeast Asia and the western North Pacific and not statistically significant, suggesting that the response of precipitation to global warming in East Asia was less robust in this experiment.

2) EFFECT OF SPATIAL NONUNIFORMITY OF SST WARMING

To confirm these responses, we examined the differences between the GW and the SST + 4 K experiments (GW-SST + 4 K), extracting the effects of the El Niño-like SST pattern (Figs. 12c,f). Both responses were normalized as described above. We could not find systematic signals of precipitation and low-level circulation along the monsoon trough. The spatial pattern of the differences in precipitation and monsoon westerlies between GW and SST + 4 K experiments along the monsoon trough was quite different from those between the CTL and GW experiments, suggesting El Niño-like SST pattern did not contribute the responses along the monsoon trough. However, circulation anomalies and increased precipitation over South Asia partly contributed to differences between the CTL and GW experiments.

Thus, the spatial patterns of precipitation differences between CTL and GW can mainly be explained by the globally uniform SST warming pattern, particularly over Southeast Asia and the western North Pacific. This finding implies that the impact of the El Niño-like SST pattern on

FIG. 12. As in Fig. 2, but we plotted the larger domain for (a) precipitation and (d) 850-hPa winds and precipitation. (b),(e) As in (a) and (d), but for the difference between the SST + 4 K and CTL [(SST + 4 K) - CTL]. Because the sample number of SST + 4 K is only 5 years, we used only 5 years for both SST + 4 K and CTL. Thus, the plots were somewhat deviated relative to (a) and (d). (c),(f) As in (a) and (d), but for the difference between GW and SST + 4 K [GW - (SST + 4 K)]. For (c) and (f), because the global mean warming values are different between GW and SST + 4 K, we normalized the responses on the basis of the respective global mean warming values (surface air temperature) before the calculation of the differences. The hatched area in (a), (b), and (c) indicates that the difference is statistically significant at the 95%, 90%, and 90% confidence level (two-sided Student's t test), respectively. The black vectors in (d), (e), and (f) indicate that the difference is statistically significant at the 95%, 90%, and 90% confidence level (two-sided Student's t test), respectively. Gray vectors in (d), (e), and (f) are not statistically significant but are plotted to understand the spatial pattern of the differences.

FIG. 12. (Continued)

Southeast Asia and part of the western North Pacific was weak in our experiments. However, these results also imply that precipitation and monsoon circulation responses are sensitive to the El Niño-like SST pattern, particularly over South Asia. Therefore, although the great importance of the spatial pattern of SST is widely accepted, we must continue to explore the major drivers of projected regional monsoon precipitation. Besides, other possible drivers, such as aerosols and

land surface conditions, may modify the spatial pattern of Asian monsoon precipitation (e.g., [Lau et al. 2017](#); [Takahashi et al. 2018](#)).

5. Conclusions

In this study, we investigated the precipitation response to global warming over the Asian monsoon region, focusing on the responses in the area of the

monsoon trough and that of the monsoon westerlies. We used a 30-yr-long set of climate simulations obtained under present-day and warmer climate conditions using NICAM with explicit convection calculations. We also analyzed tropical disturbance activity using PKE at 850 hPa, because the observational evidence showed that precipitation variation over the South and Southeast Asian monsoon regions was associated with tropical disturbances.

The simulated results were evaluated by the observational datasets. The spatial and seasonal evolutions and peaks in precipitation and monsoon westerly, including the monsoon onset and monsoon trough, were simulated in the NICAM, which implies that significant components of the Asian monsoon could be reproduced. Besides, the tropical disturbances with precipitation were simulated along the monsoon trough. However, the northward displacement biases of the monsoon westerly and precipitation were found, which is expected to improve in the future.

Our results showed that precipitation generally increased over the Asian monsoon region due to global warming with regional variation. Precipitation mainly increased along with a zonally elongated band across part of India, the Bay of Bengal, the South China Sea, and the western and central Pacific, which corresponded to the monsoon trough and part of the ITCZ. This increased precipitation was likely due to an increase in precipitable water. The spatial pattern of the increased precipitation was consistent with the enhanced cyclonic circulation with enhanced vertical motion along the monsoon trough. However, because the strengthening or weakening of the large-scale monsoon westerlies were unclear, we could not conclude the future changes in the large-scale monsoon westerlies. The future changes in the monsoon westerly should be continued to study. Regional differences in precipitation associated with enhanced cyclonic anomaly and vertical motion can be explained by strengthened tropical disturbance activity along the monsoon trough. Thus, the contributions of precipitation associated with the tropical disturbance activity are essential for understanding future changes in precipitation over the Asian monsoon region.

We then decomposed the responses in precipitation and winds into the effects of the uniform global warming and changes in the spatial SST pattern. The impact of uniform global warming mainly explained increased precipitation with cyclonic circulation anomalies along the monsoon trough. Over part of South Asia, the spatial SST pattern likely contributed to the increased precipitation. These results imply that there are different regional responses, which can be related to the basic climatological precipitation systems.

Also, the precipitation and precipitable water increased more along the axis of the monsoon trough,

which can be understood as the concentration of water vapor and precipitation on the monsoon trough. We calculated the change rate of column-integrated water vapor per 1-K warming at each grid and found that the increased water vapor rate considerably exceeded 6%–7% over the area where precipitation increased. This increase in water vapor was far from spatially uniform, even over oceans. The different regional responses of water vapor can be explained by the future changes of low-level circulations, suggesting a coupling dynamics and thermodynamics effects along the monsoon trough.

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